Analysis of $K_L \rightarrow \pi^{\pm} e^{\mp} \nu e^{+} e^{-}$ (Ke3ee)

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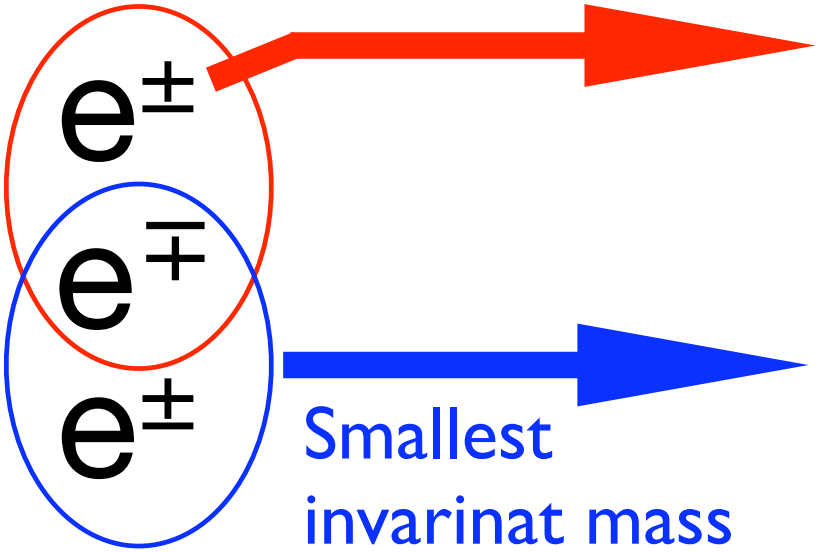
at FNAL
Katsushige Kotera
from Osaka University

Just Definition

$K_L \rightarrow \pi^{\pm} e^{\mp} \nu e^{+} e^{-}$



$e^{\pm}$ from Ke3
($e^{\pm}_{Ke3}$)

$e^{\mp}$
$e^{\pm}$
} from pair
($e^{\pm}_{pair}$)

Assumptions

Data	'97 winter; NZF003-038
Trigger	Trigger 4 (Four track TRG)
KTeVMC	version 6.00
KTeVANA	version 6.00
Ke3ee gnerator	ChPT[NLO(p^4)]
Radiative correction	PHOTOS v.2.13 (binomial)
Normalization mode	$K_L \rightarrow \pi^+\pi^-\pi^0{}_D$

Backgrounds

- $K_L \to \pi^+\pi^-\pi^0_D$ $(\pi^0 \to e^+e^-\gamma)$

  ↓

  One $\pi^\pm$ fakes $e^\pm$

Important
π-e rejection !

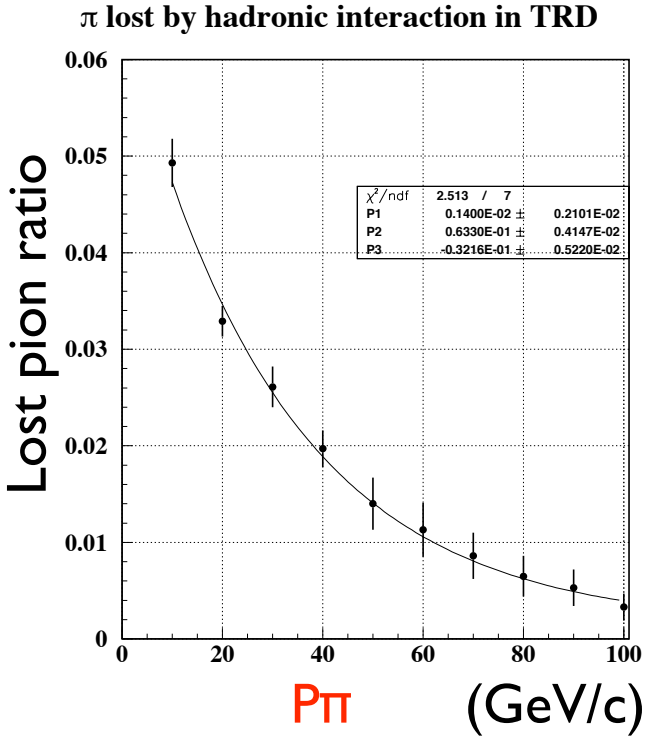
- $K_L \to \pi^\pm e^+\nu\ \pi^0_D$ $(\pi^0 \to e^+e^-\gamma)$
- $K_L \to \pi^\pm e^+\nu\ \gamma$ $(\gamma \to e^+e^-$: external conversion)
- $K_L \to \pi^+\pi^-\pi^0_{4e}$ $(\pi^0 \to e^+e^-e^+e^-)$
  - double Ke3
  - $\Xi \to \Lambda(\to P\pi^-)\pi^0_D$

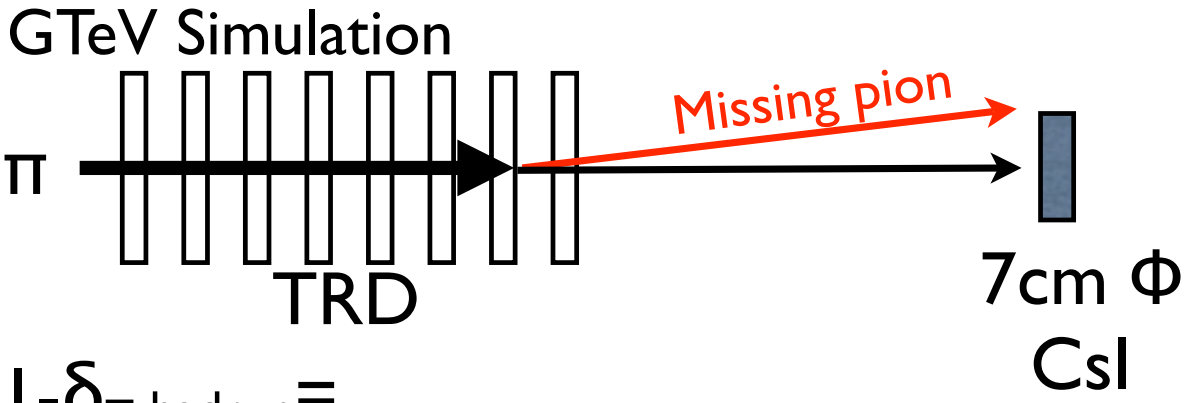
Modified parts of MC

- Weighted for lost pion in TRD
  by pion-hadron interactions
- Tuned E_k distribution by $\pi^+\pi^-\pi^0{}_D$ data
- e+e- conversion of photon
  in detector × 10
- π-e fake rate × 1.5

Modified points on MC

- Weighted for lost pion in TRD by pion-hadron interactions





$1-\delta_{\pi\text{-hadron}} = 1-(A\, e^{-B P_\pi} - C)\times L_{TRD}/L_{TRD0}$

L_{TRD} :Path length in TRD

L_{TRD0} :Length of TRD

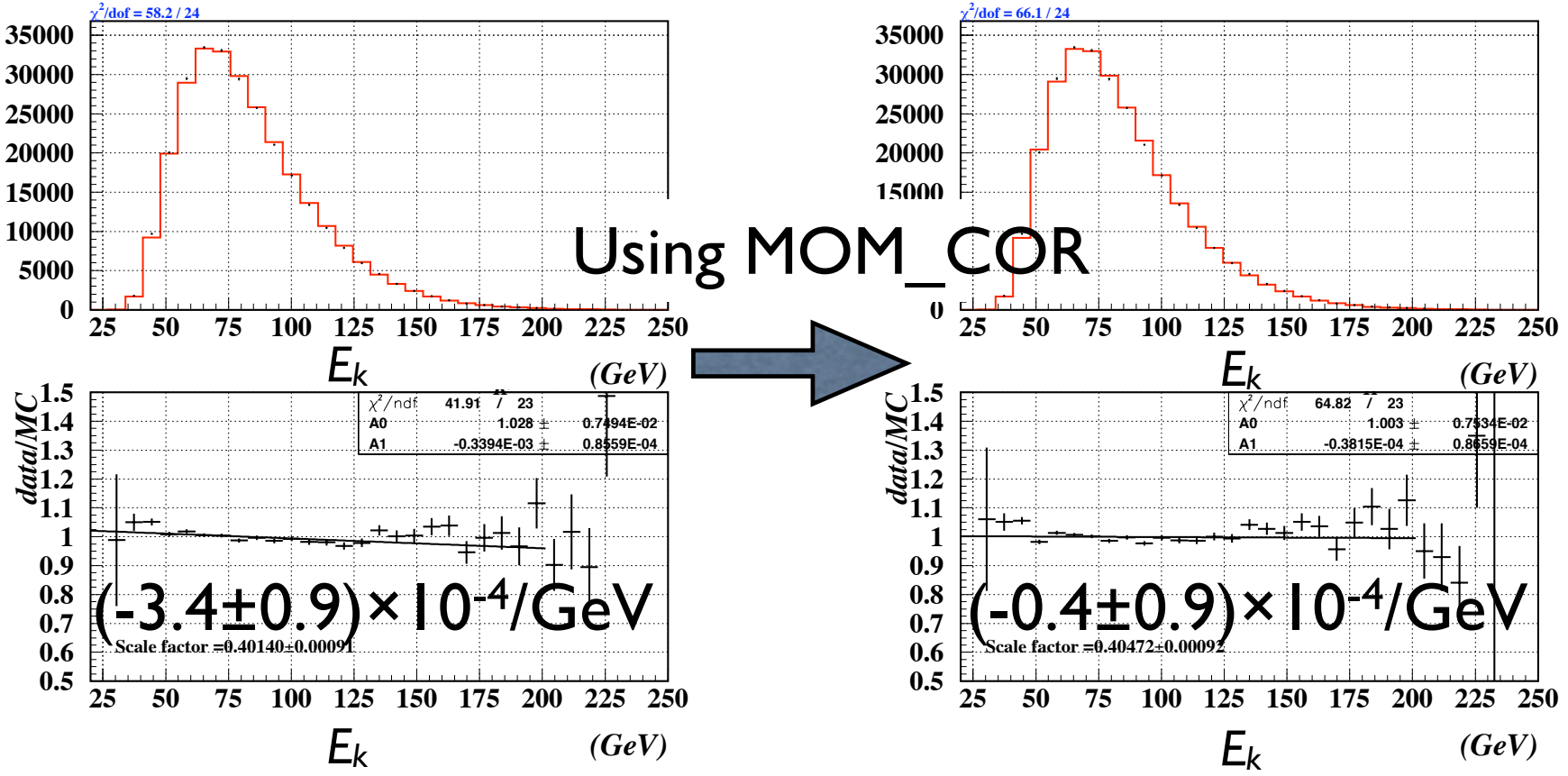
Modified points on MC

- Weighted for lost pion in TRD
  by pion-hadron interactions
- Tuned E_k distribution by $\pi^+\pi^-\pi^0{}_D$ data
- e+e- conversion of photon
  in detector × 10
- π-e fake rate × 1.5

Modified points on MC

- Tuned E_k distribution by $\pi^+\pi^-\pi^0_D$ data

  $\pi^+\pi^-e^+e^-\gamma$ full reconstraction



Modified points on MC

- Weighted for lost pion in TRD
  by pion-hadron interactions
- Tuned E_k distribution by $\pi^+\pi^-\pi^0{}_D$ data
- e+e- conversion of photon
  in detector × 10
- π-e fake rate × 1.5

Modified points on MC

- e+e- conversion of photon in detector × 10

for $K_L \to \pi^{\pm} e^{+} \nu \gamma$, $K_L \to \pi^{+}\pi^{-}(\pi^0 \to \gamma\gamma)$

To save the generation time conversion probability × 10

The number of generated events

$$\frac{\square}{\#\ \text{conversion}} = \frac{\#\ \text{generated}}{\#\ \text{conversion}}$$

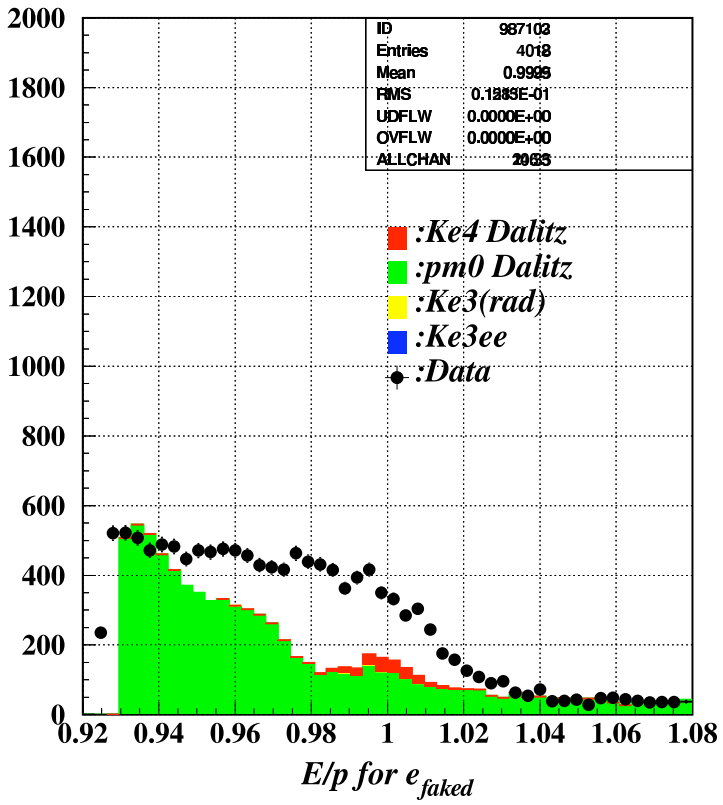
(default MC)

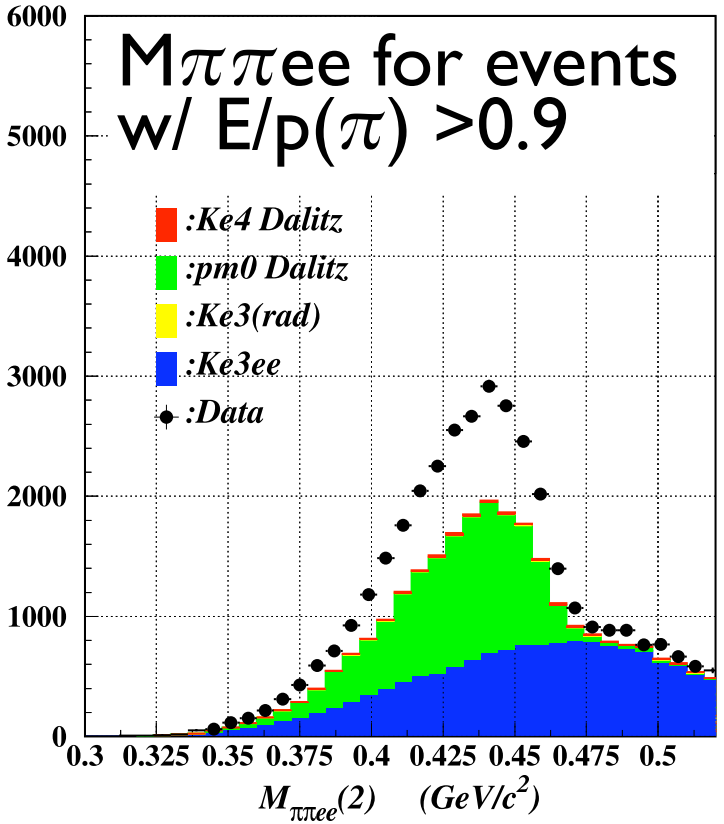
Modified points on MC

- Weighted for lost pion in TRD
  by pion-hadron interactions
- Tuned E_k distribution by $\pi^+\pi^-\pi^0{}_D$ data
- e+e- conversion of photon
  in detector × 10
- π-e fake rate × 1.5

Modified points on MC

- π-e fake rate × 1.5
  Data-MC discrepancy is 1.5





Cuts for signal

Fiducial

vertex χ^2 <125
Ek max < 200 GeV
95 < Z-vertex < 150 m
Track energy
E_{π} > 10 GeV
Ee_{ke3} > 10 GeV
Ee_{pair} > 3 GeV

Invariant mass

Mee > 0.005 GeV/c^2
Mπeee < 0.5 GeV/c^2

Particle ID

0.93 < *E*/*p* $e^{\pm}$ < 1.15
E/*p* $\pi^{\pm}$ < 0.9
TRD probπ for $e^{\pm}$ < 0.06

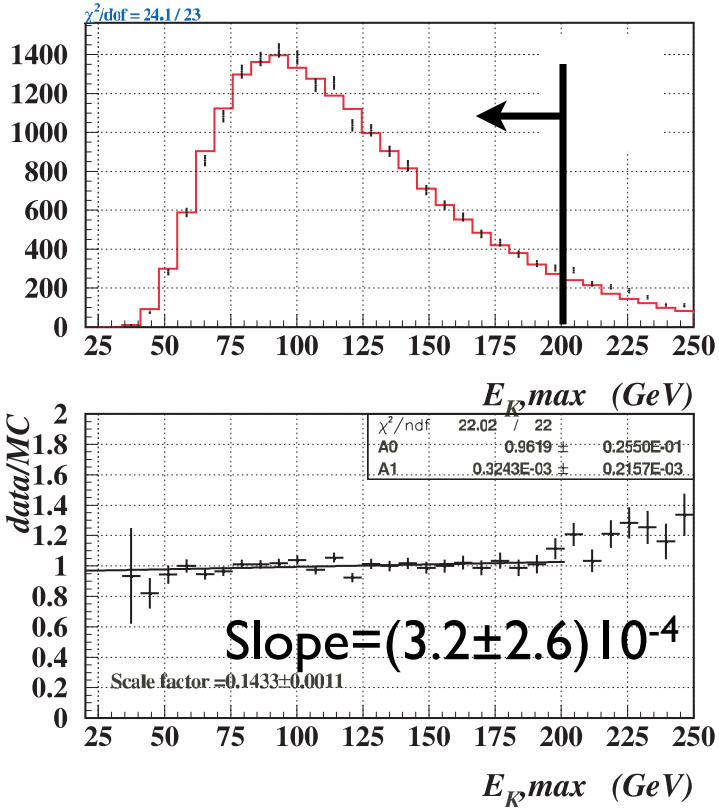
Kinematical

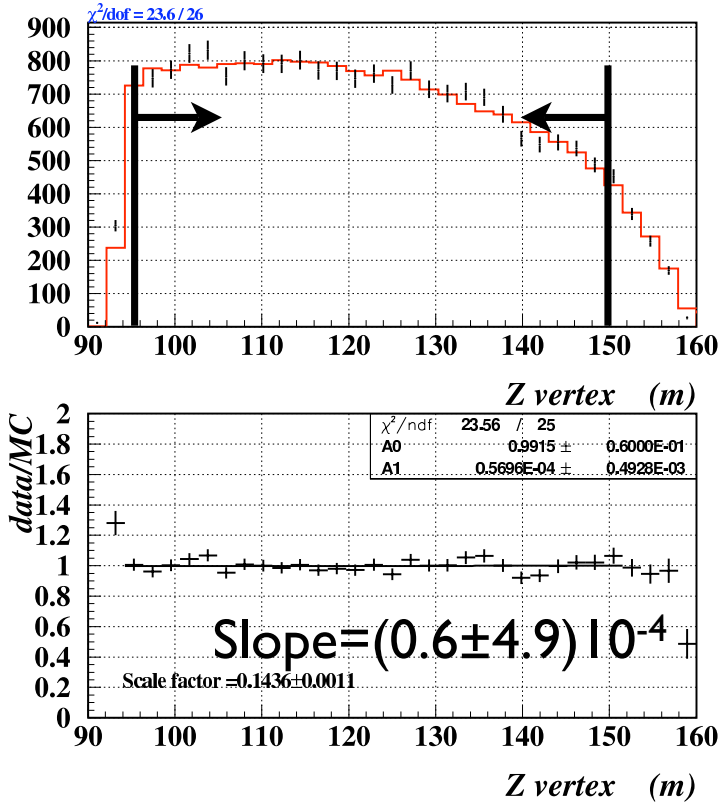
pp0kin < -0.002 GeV^2/c^2
$P_{\nu ll}{}^{*2}$ $P_{\nu ll}{}^{*2}$ > 0 GeV/c^2

Additional

No cross tracks in the x view of TRD

Fiducial cuts: *Ek, Z-vtx*

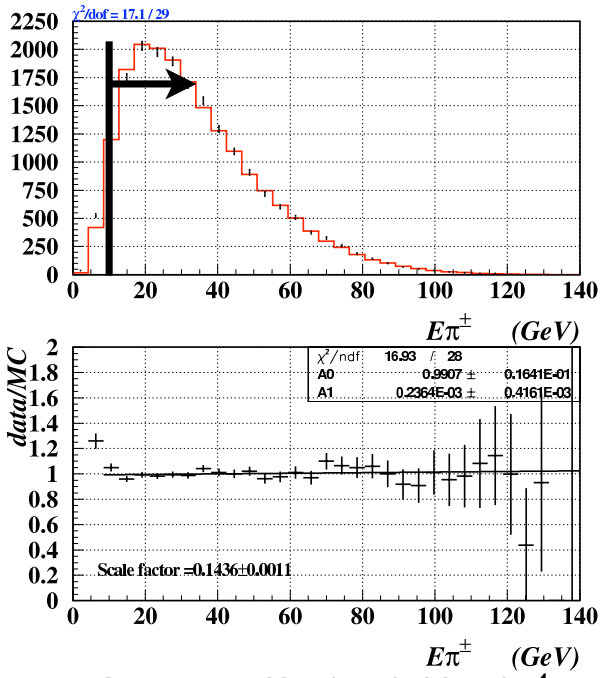




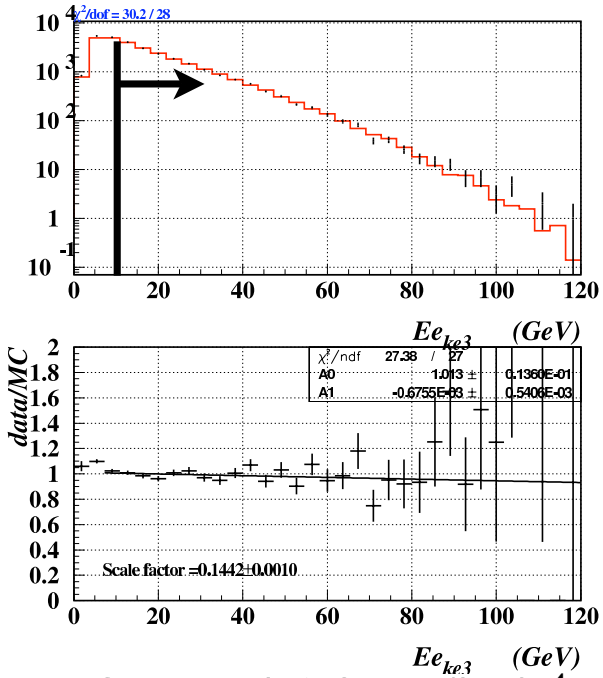
Ek < 200 GeV

95 < Z-vtx < 150 m

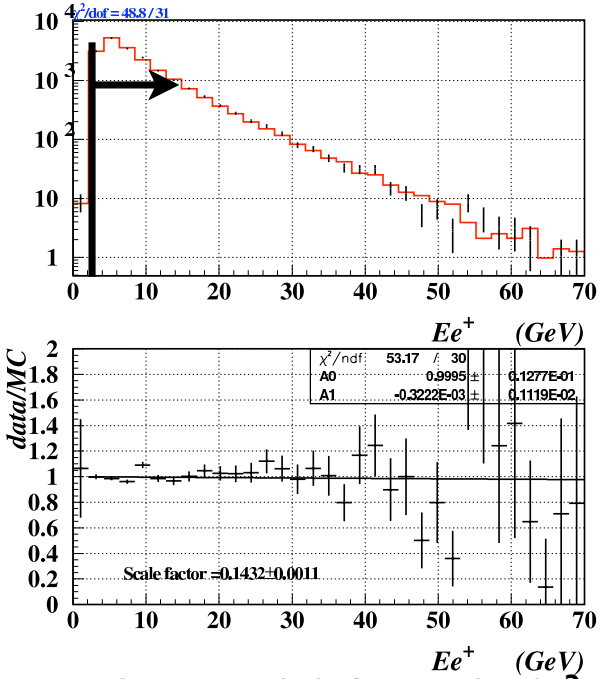
Particle energies in Lab: *Eπ*, *Ee*



Slope=(2.4±4.2)10^{-4}



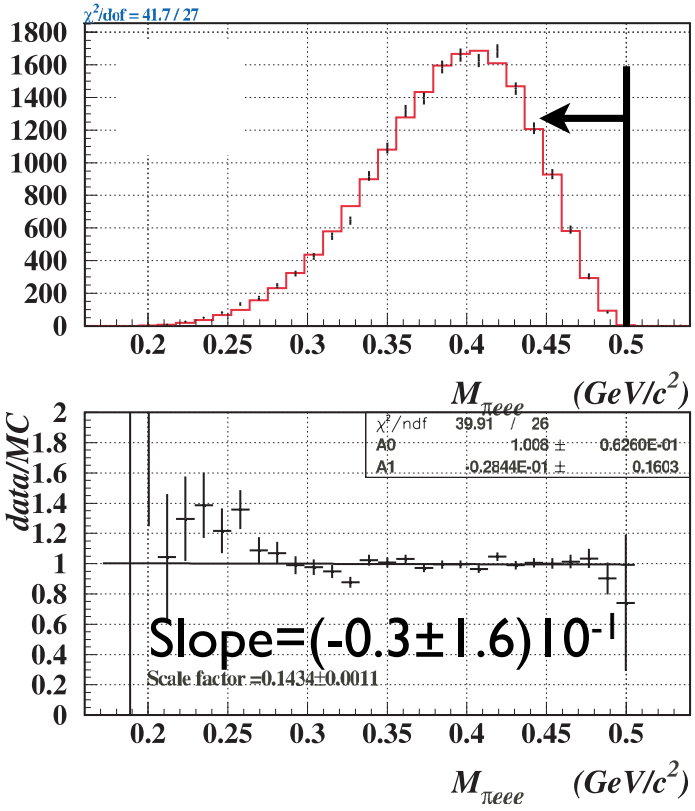
Slope=(-6.8±5.4)10^{-4}

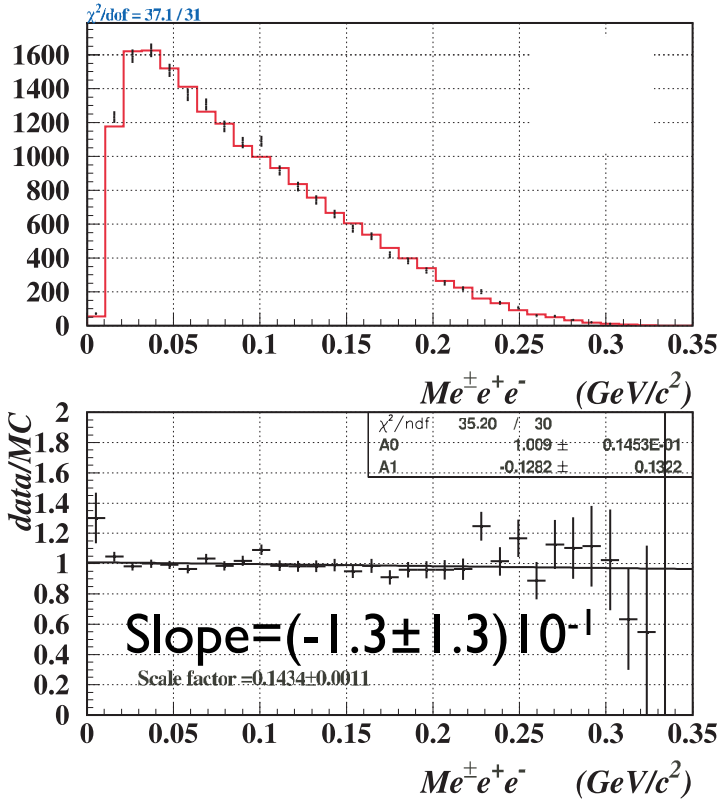


Slope=(-0.3±1.1)10^{-3}

Eπ > 10 GeV *Ee$_{ke3}$* > 10 GeV *Ee$_{pair}$* > 3 GeV

Invariant Mass; *M*πeee, *M*eee

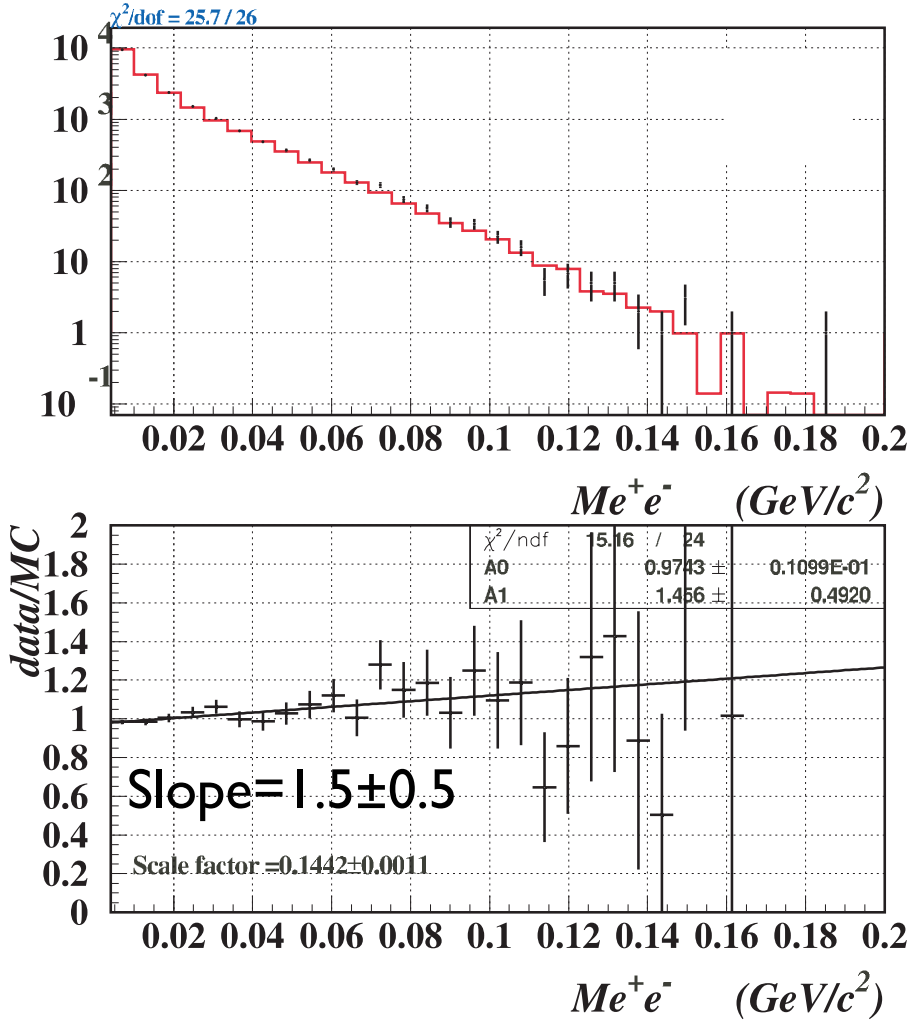




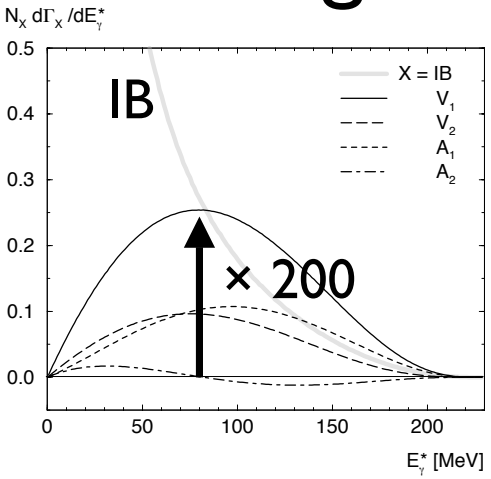
*M*πeee < 0.5 GeV/c²

*M*eee; no cut

Invariant Mass; Me^+e^-

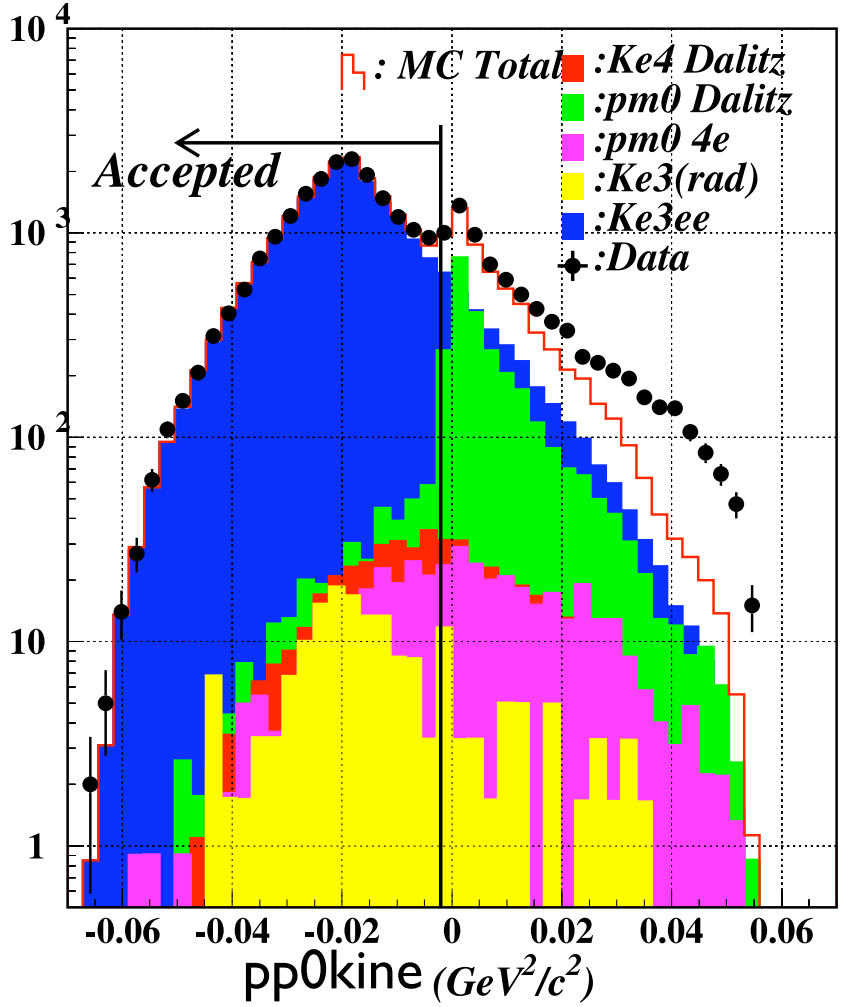


- $Me^+e^- > -0.005$ GeV/c^2
- This is cut-off value of our BR(ke3ee)
- Only this spectrum has a significant slope



An example of terms of $E\gamma^*$ of Ke3γ by Gasser et al.

Rejection of $K \to \pi^+\pi^-\pi^0$

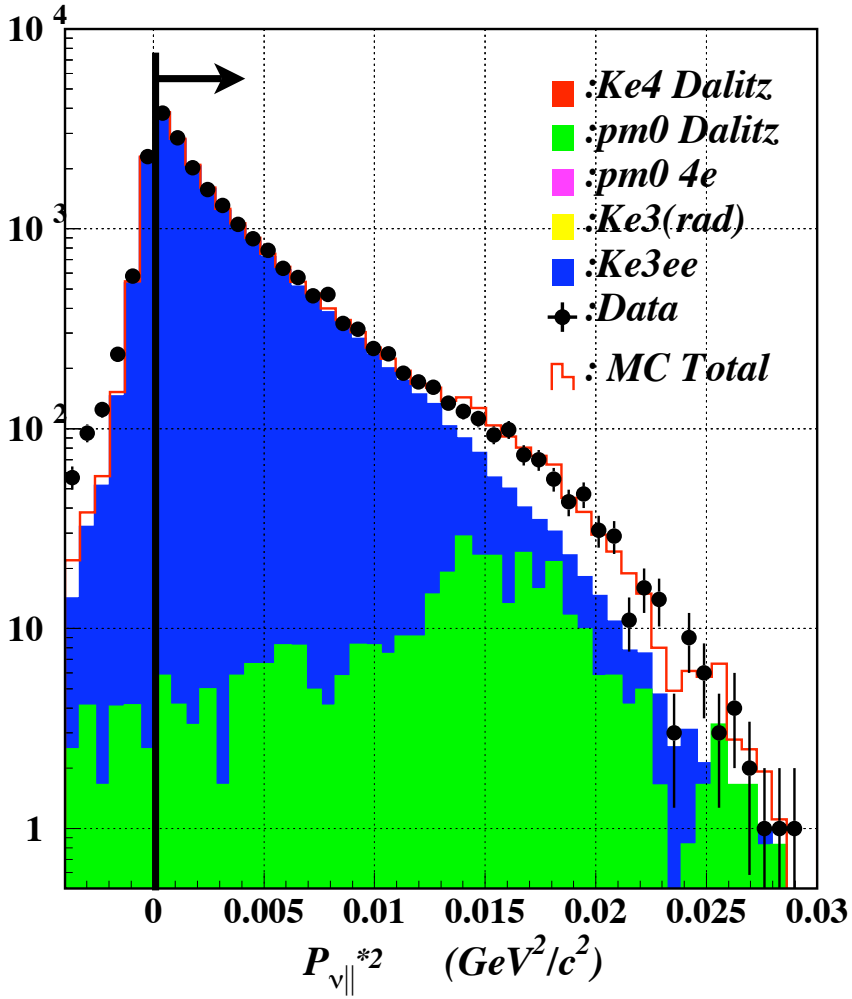


86.6% $K \to \pi^+\pi^-\pi^0_D$ is rejected

57.3% $K \to \pi^+\pi^-\pi^0_{4e}$ is rejected

15.6% Ke3ee is rejected

BG $K_L \to \pi^+\pi^-(\pi^0 \to e^+e^-\gamma)$ $P_{v||}{}^{*2}$

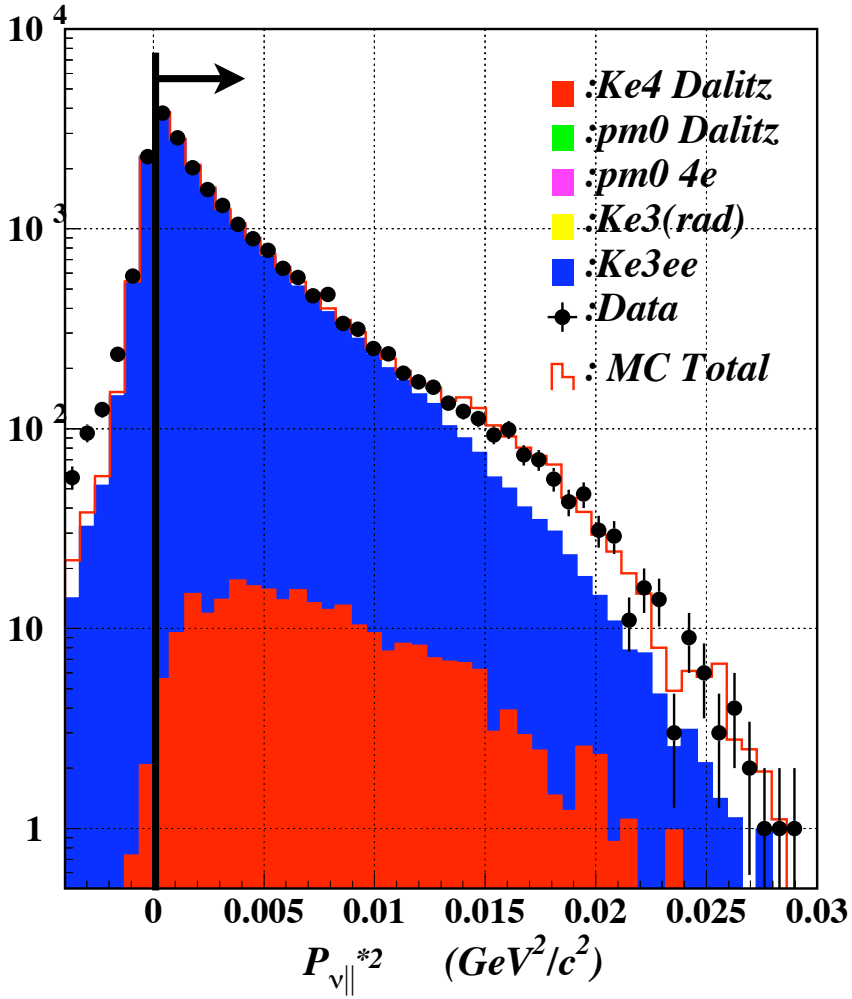


$K_L \to \pi^+\pi^-(\pi^0 \to e^+e^-\gamma)$ / signal

= 322.60 / 19466

1.66%

BG $K_L \to \pi^{\pm} e^{\mp} \nu(\pi^0 \to e^+ e^- \gamma)$ $P_{\nu\parallel}{}^{*2}$

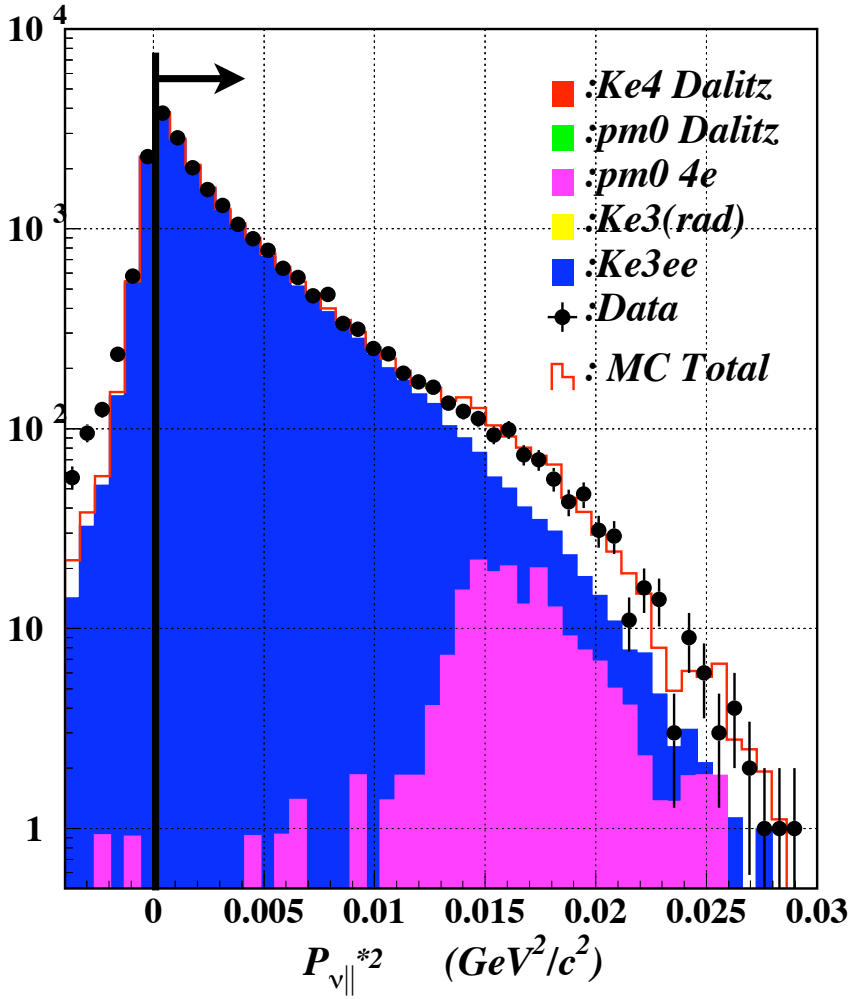


$K_L \to \pi^{\pm} e^{\mp} \nu(\pi^0 \to e^+ e^- \gamma)$ / signal

= 268.74 / 19466

1.38%

BG $K_L \to \pi^+\pi^-(\pi^0 \to e^+e^-e^+e^-)$ $P_{\nu\|}{}^{*2}$



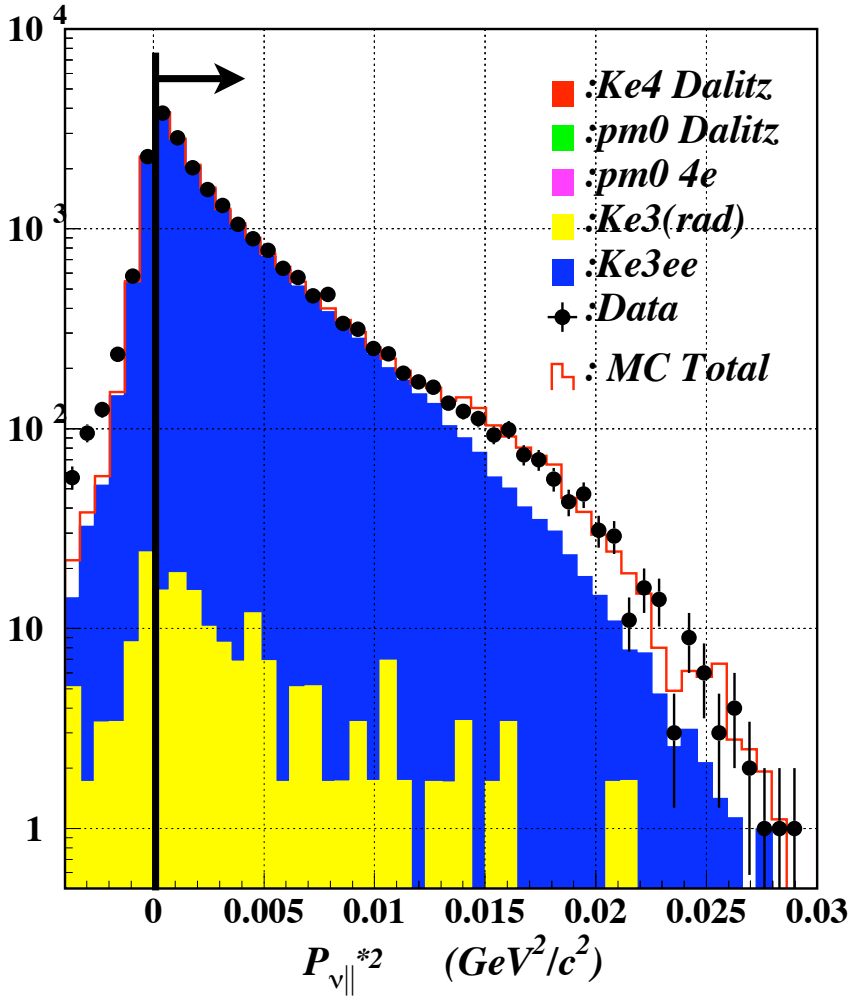
$K_L \to \pi^+\pi^-(\pi^0 \to 4e)$

/ signal

= 191.68 / 19466

0.98%

BG $K_{e3}(\gamma \rightarrow e^+e^-$:external) $P_{\nu\|}{}^{*2}$



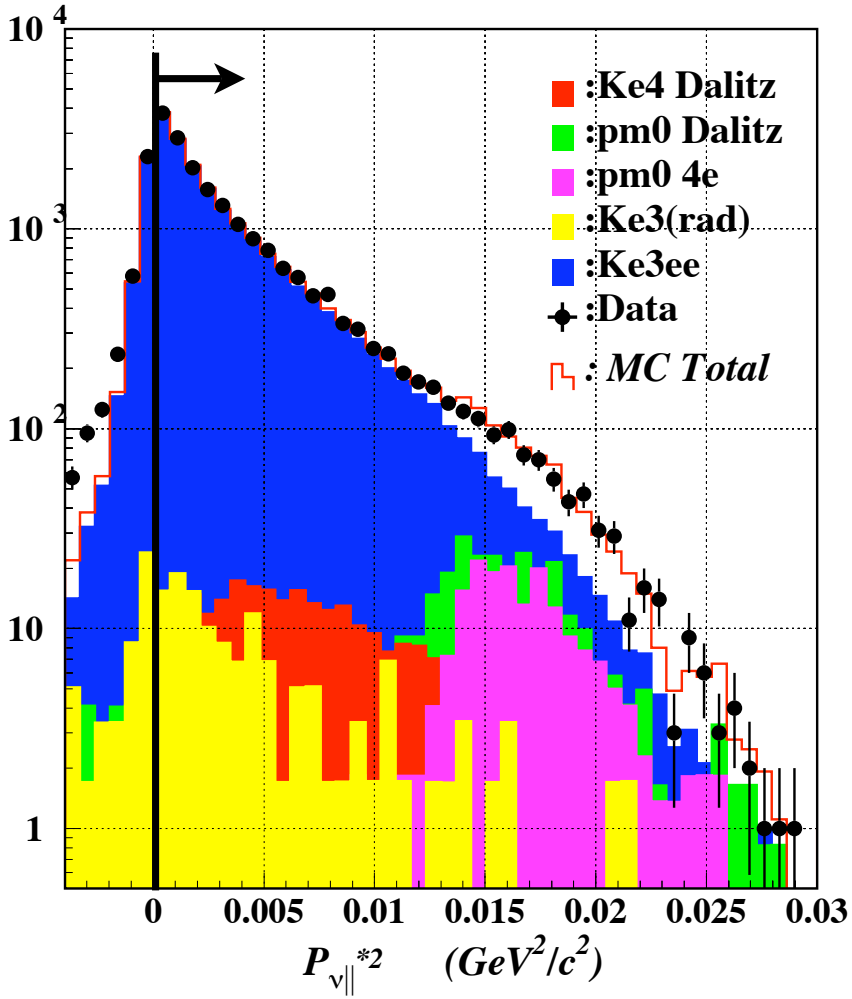
$K_L \rightarrow K_{e3}(\gamma \rightarrow e^+e^-$:ext.)

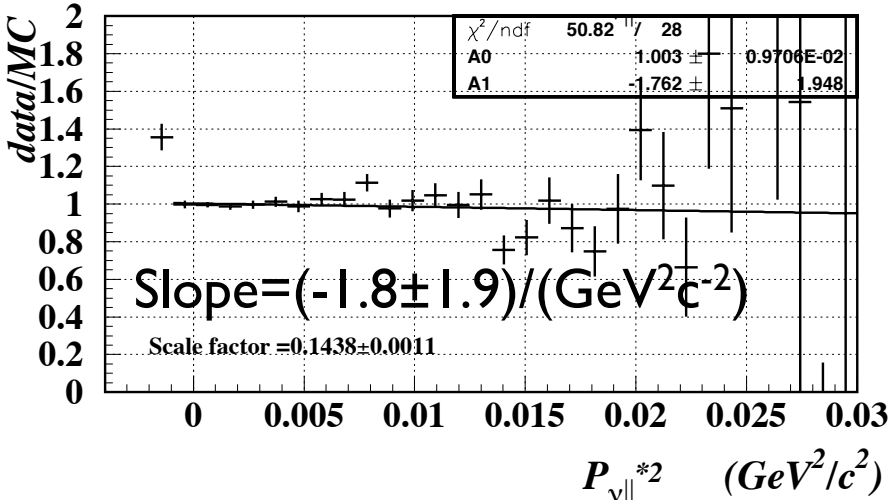
/ signal

= 138.34 / 19466

0.71%

Data-MC comparison of $P_{\nu\|}{}^{*2}$

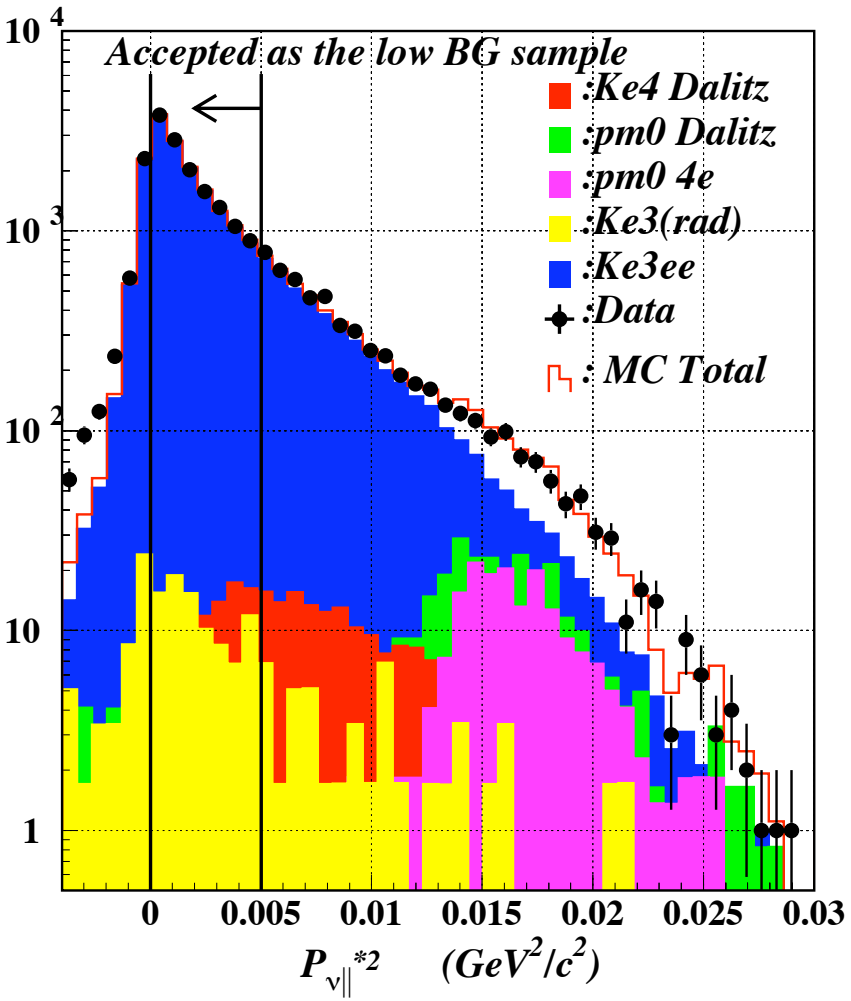




N/S total =

4.95%

Low BG sub-sample by $P_{\nu\|}{}^{*2}$



Result cross check

Decay mode	Full	Low BG
Signal(inc.BG)	19466	14081
+-0 Dalitz	322.60	31.23
Ke4 Dalitz	268.74	92.51
+-0 eeee	191.68	2.76
RadKe3(conv)	138.34	88.75
Dauble Ke3	41.37	30.47
Cascade	1.79	0.29
BG/Signal	4.95%	1.75%
Estimated # of Ke3ee × 10^{-6}	3.041±0.025	3.019±0.029

Consistent with stat. error !

Normalization mode

$K_L \rightarrow \pi^+\pi^-(\pi^0 \rightarrow e^+e^-\gamma)$

- Main

  $\pi^+\pi^-e^+e^-$ ignoring γ

- Cross check

  $\pi^+\pi^-e^+e^-\gamma$ full reconstruction

BG for norm. mode

$K_L \to \pi^+\pi^-(\pi^0 \to \gamma\gamma) \to e^+e^-$

Double Ke3 and Cascade are negligible.

Cuts for normalization mode

Only different point from signal analysis

$pp0kin < -0.002\ GeV^2/c^2 \longrightarrow pp0kin > -0.002\ GeV^2/c^2$

missing particle = neutrino $\longrightarrow$ missing particle = photon

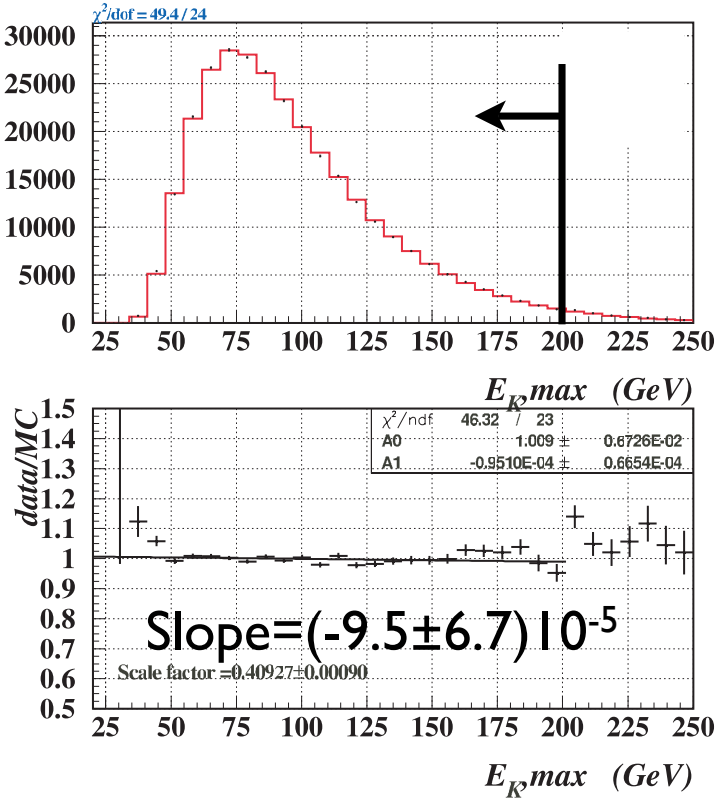
$Ee_{ke3} \longrightarrow E\pi_{(another)}$

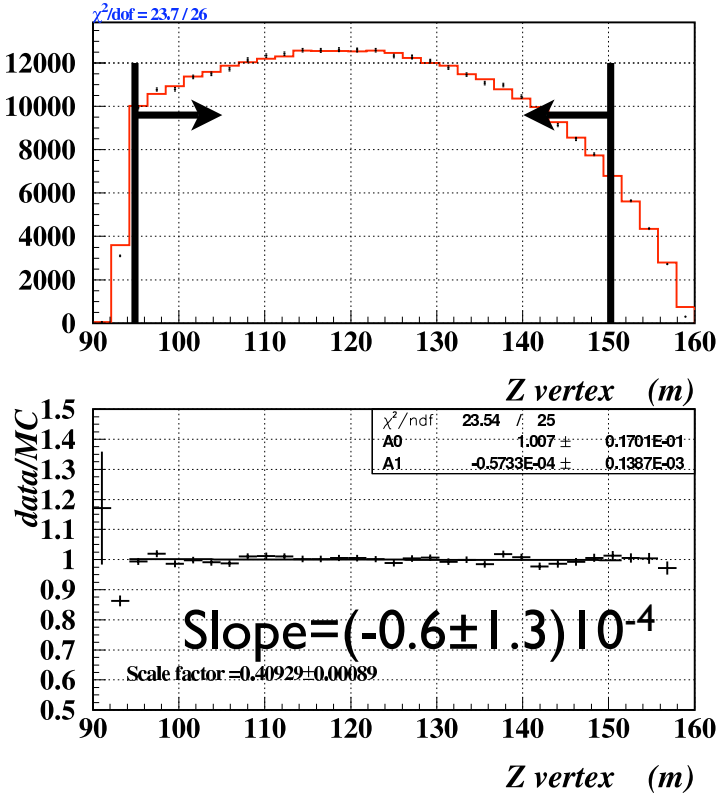
Additional cuts for only full reconstruction analysis

$0.492 < M\pi\pi ee\gamma < 0.508\ GeV/c^2$

$0.127 < Mee\gamma < 0.143\ GeV/c^2$

Fiducial cuts: *Ek, Z-vtx*

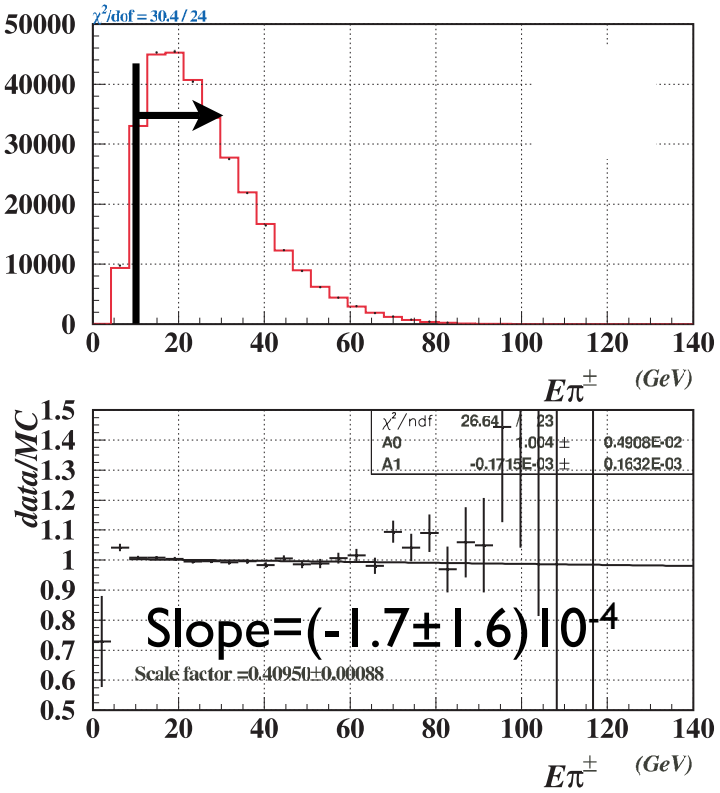




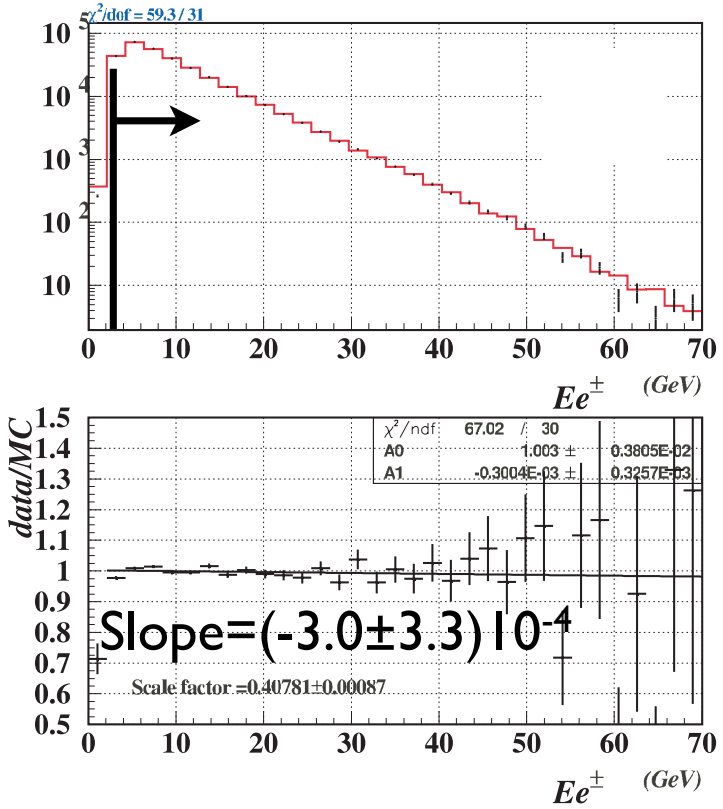
Ek < 200 GeV

95 < Z-vtx < 150 m

Particle energies in Lab: *Eπ*, *Ee*

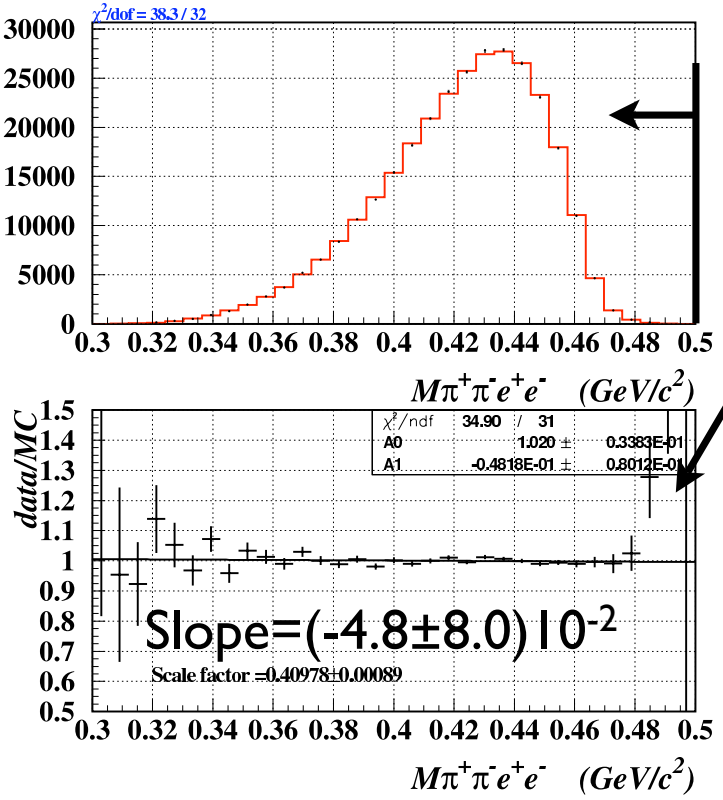


Eπ > 10 GeV



Ee > 3 GeV

Invariant Mass; *Mππee*

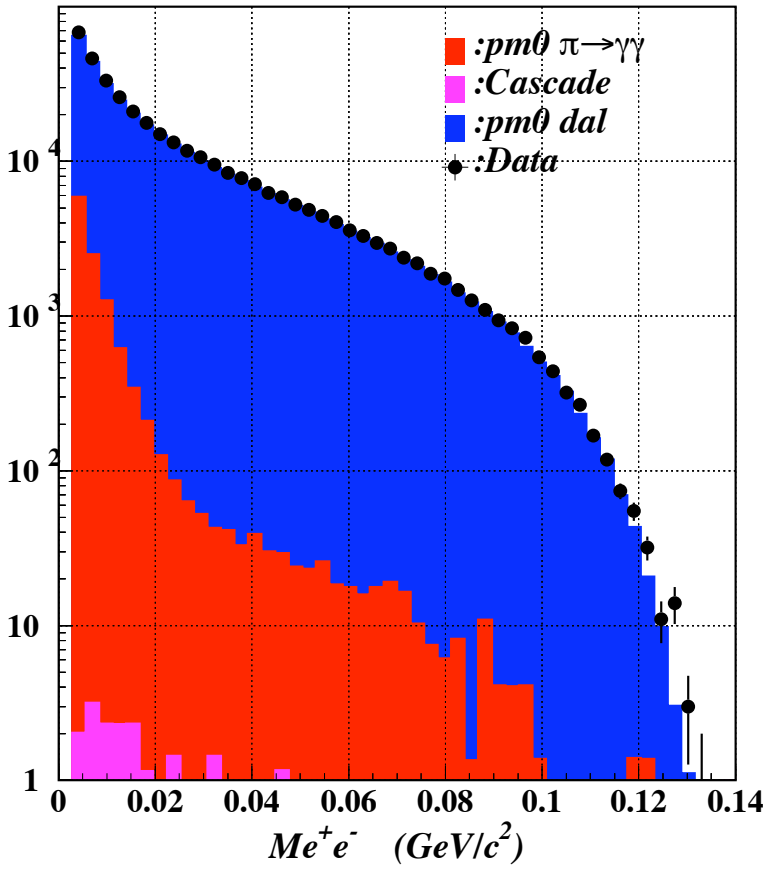


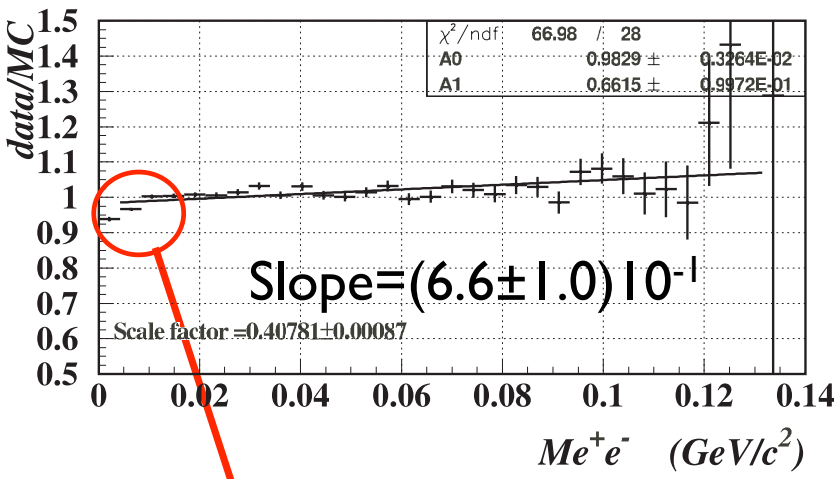
Negligiblly small effect

Not $K_L \rightarrow \pi^+\pi^-e^+e^-$, because it is suppressed by pp0kine

Mππee < 0.5 GeV/c^2

Invariant Mass; *Mee*





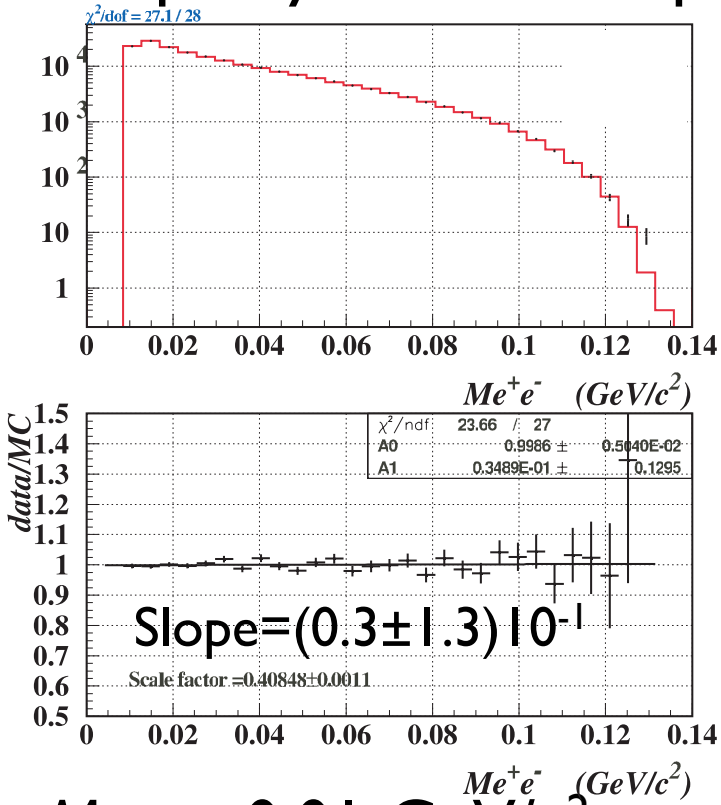
$K_L \rightarrow \pi^+\pi^-(\pi^0 \rightarrow \gamma\gamma) \rightarrow e^+e^-$

Not high quality

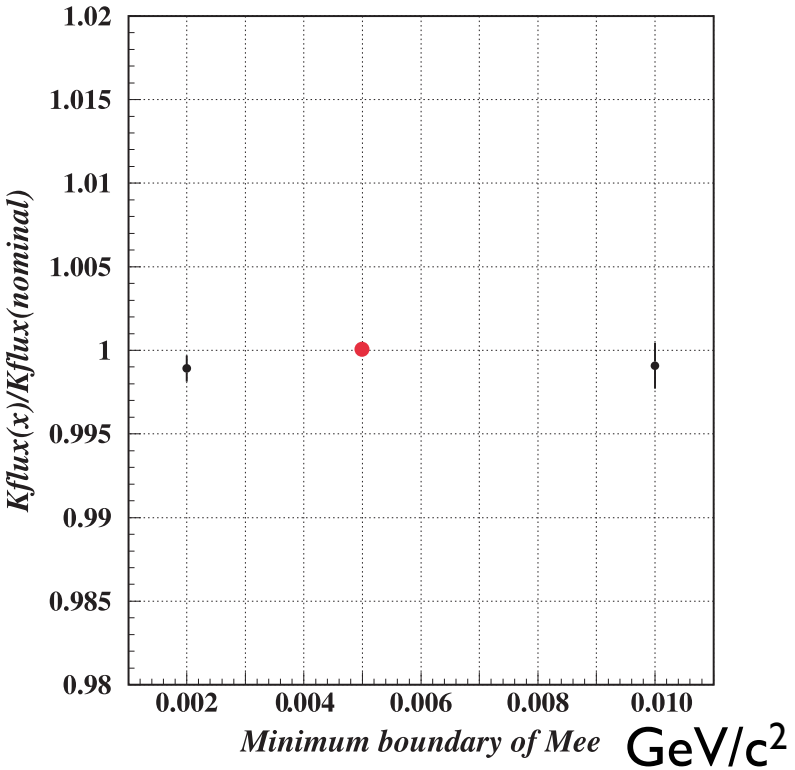
Mee > 0.005 GeV/c^2

Invariant Mass; *Mee*

Discrepancy due to MC pmzgg



Effect on K-flux is negligible



Mee > 0.01 GeV/c^2

0.127 < Meeγ < 0.143 GeV/c^2

without Meeγ cut

Kaon flux

300526 : signal

6690.64 : +-$0_{\gamma\gamma}$ background

[20 < *Ek* < 220 GeV, 90 < Z-vtx < 160]

K flux : $(1.682 \pm 0.004) \times 10^{11}$: too large ?

↓ with out 'π loss in TRD' correction

K flux : $(1.599 \pm 0.004) \times 10^{11}$: comparable ?

Systematic uncertainties(%)

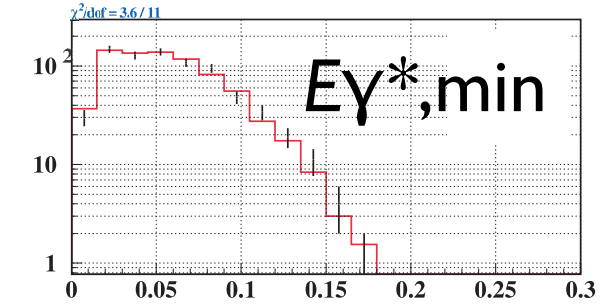
Source of uncertainty	(%)
Radiative corrections	+1.00
Photon det. in norm.	+0.83
vertex χ^2	±0.70
π loss in TRD	±0.47
E_K distribution	- 0.35
Cut-off Mee	- 0.18
$e^{\pm}$ ineff. in E/p	±0.08

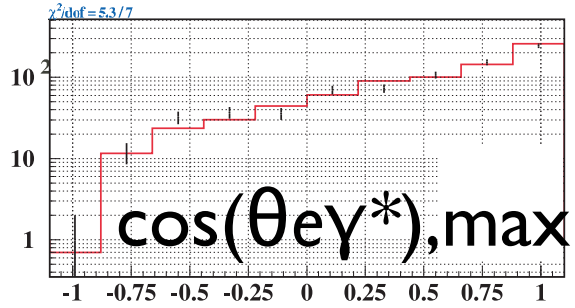
Source of uncertainty	(%)
$e^{\pm}$ ineff. in TRD	±0.08
$\pi^{\pm}$ ineff. in E/p	±0.03
BG. Ke3γ	±0.07
BG. K_{+-0} Dalitz	±0.04
MC stat. Ke3ee	±0.27
MC stat. BG.	±0.14
MC stat. Norm.	±0.12

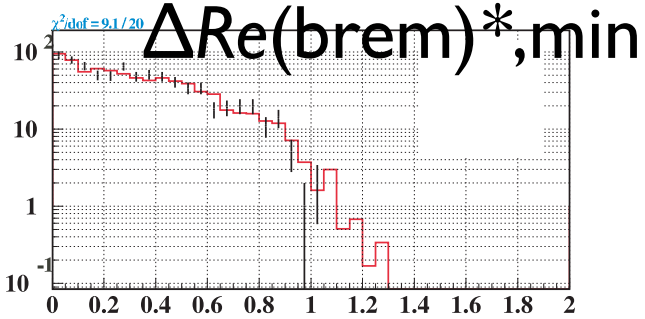
Total $^{+1.59}_{-1.00}$

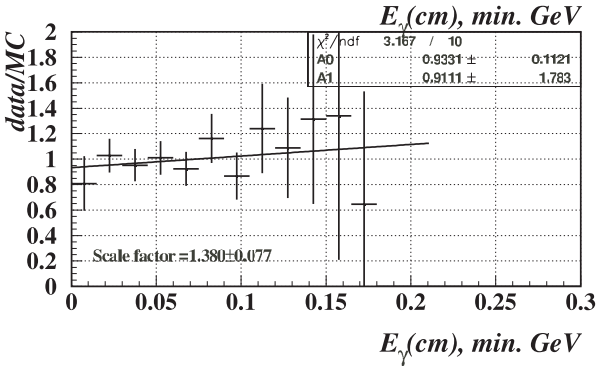
Radiative corrections(+1%)

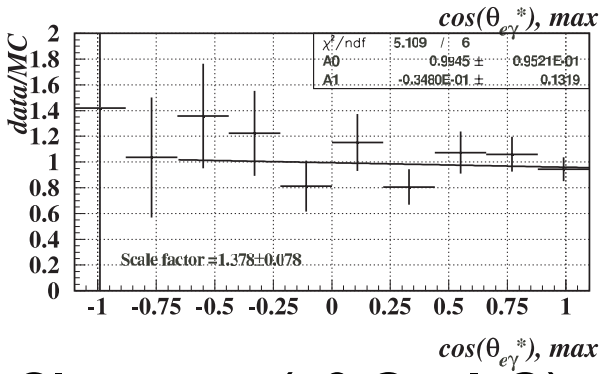
1+δrad(Ke3ee generator + PHOTOS,v.2.13) = 1.036

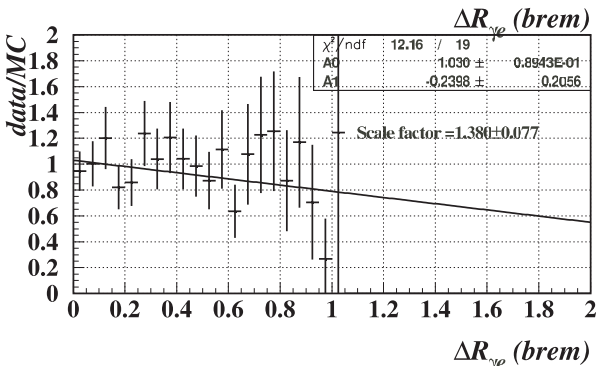












Slope = 0.9±1.8

Slope = (-0.3±1.3) ×10^{-1}

Slope = (-2.4±2.1) ×10^{-1}

Shapes well agree on data-MC, but 1.38 scale factors are needed.

→ Assuming linear effect of radiation on the acceptance

1.036 → 1.046

1.0% uncertainty

Photon candidates collection criteria

$E_\gamma > 3$ GeV
$\Delta R_{\gamma\text{-}\pi} > 0.3$ m
$\Delta R_{\gamma\text{-}e} > 0.1$ m
$\Delta R_{\gamma\text{-brem}} > 0.02$ m
Shape $\chi 2 < 20$
Small Ring >4.5
Large Ring <18.5
Early CsI ADC < 420 counts
In-time CsI ADC >200 counts
Time $\chi 2 < 100$
$E_\gamma^* < 0.18$ GeV

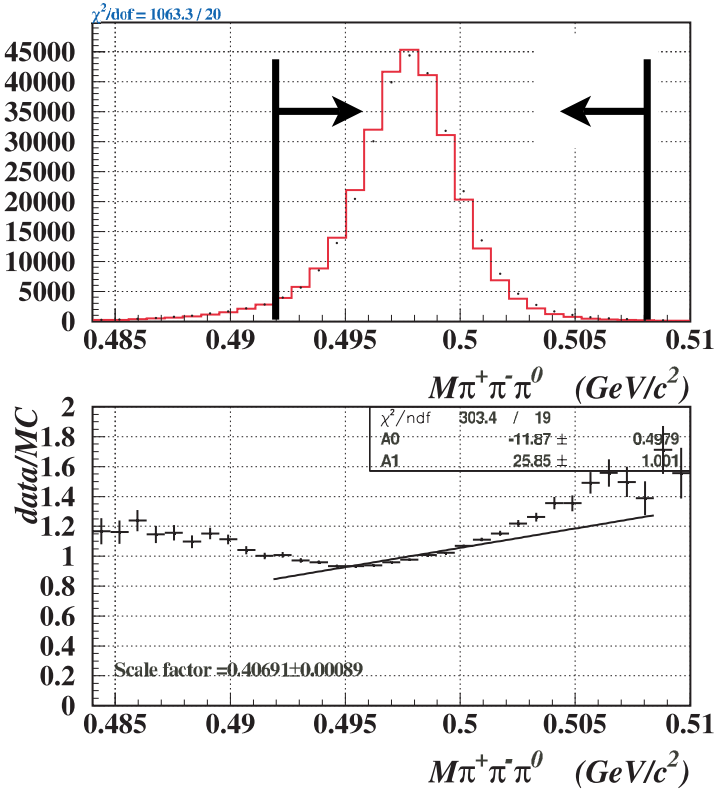
Comparison with ππeeγ(full) *ana.* K flux

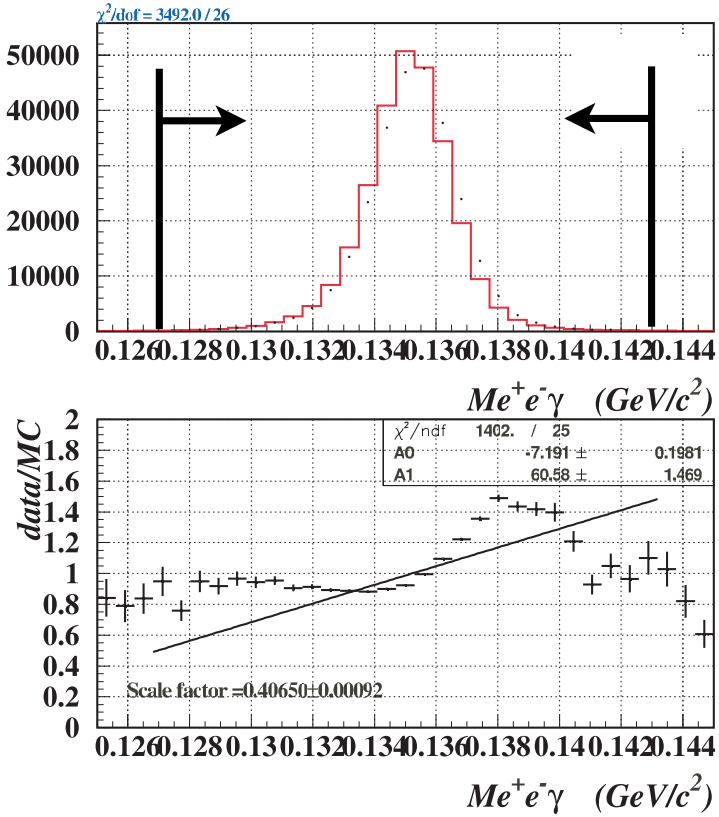
	Result	cross check
Decay mode	ππee ana (ignoring photon)	ππeeγ ana (Full reconstruction)
+-0Dalitz(inc.BG)	300526	263836
+-0 $\pi^0 \to \gamma\gamma$	6690.64	4384.60
BG/Signal	2.23%	1.66%
Estimated # of $K_L \to \pi^+\pi^-\pi^0 \times 10^{-8}$	2.7823±0.0063	2.7593±0.0066

-0.83% uncertainty on K flux

6.7 σ(stat.) significant difference between two method

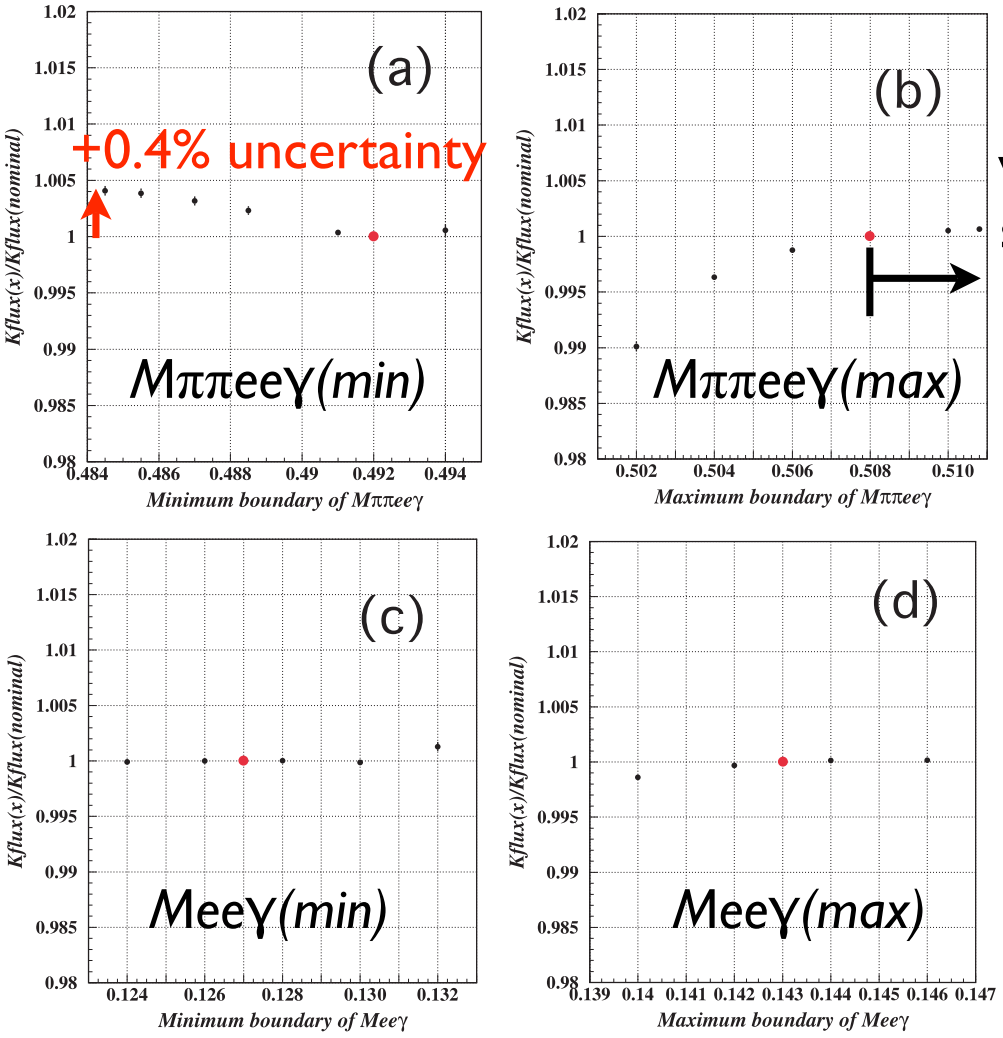
Uncertainty from ignoring the photon(+0.83%) ; $M\pi\pi ee\gamma$, $Mee\gamma$



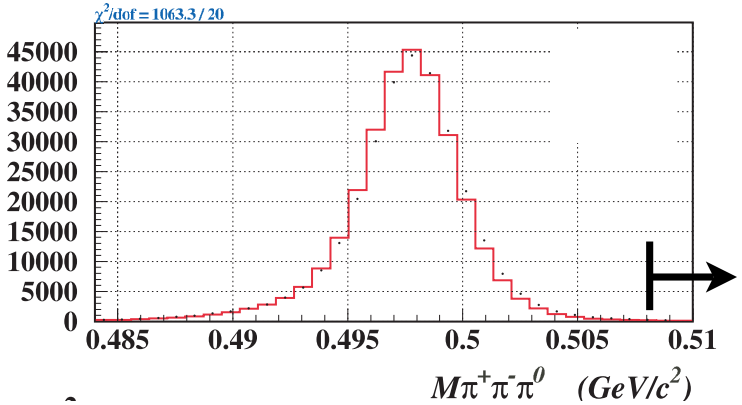


Famous discrepancies

Cuts variations of *Mππeeγ*, *Meeγ*

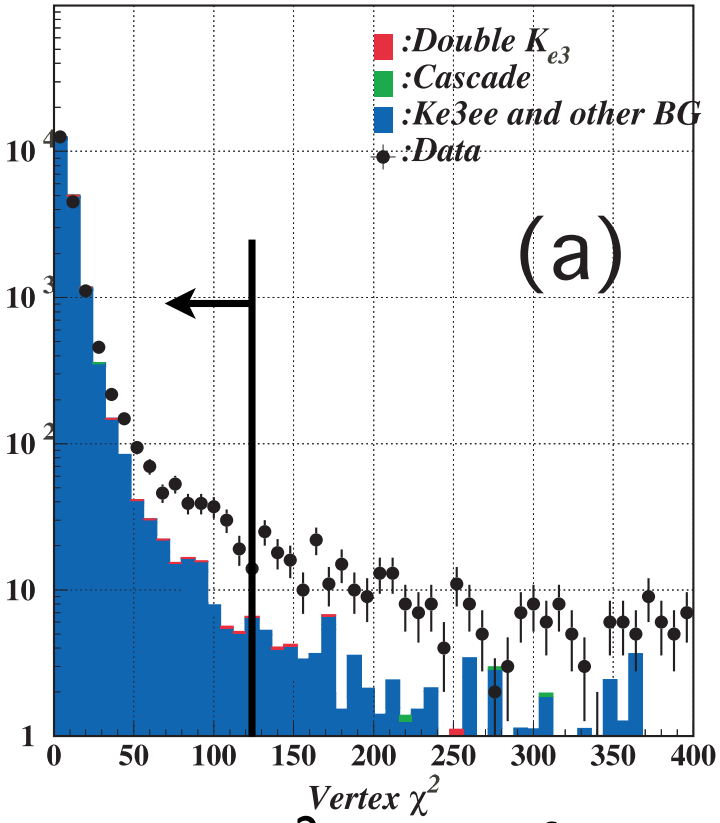


we are allowed to take spread area as we can ?

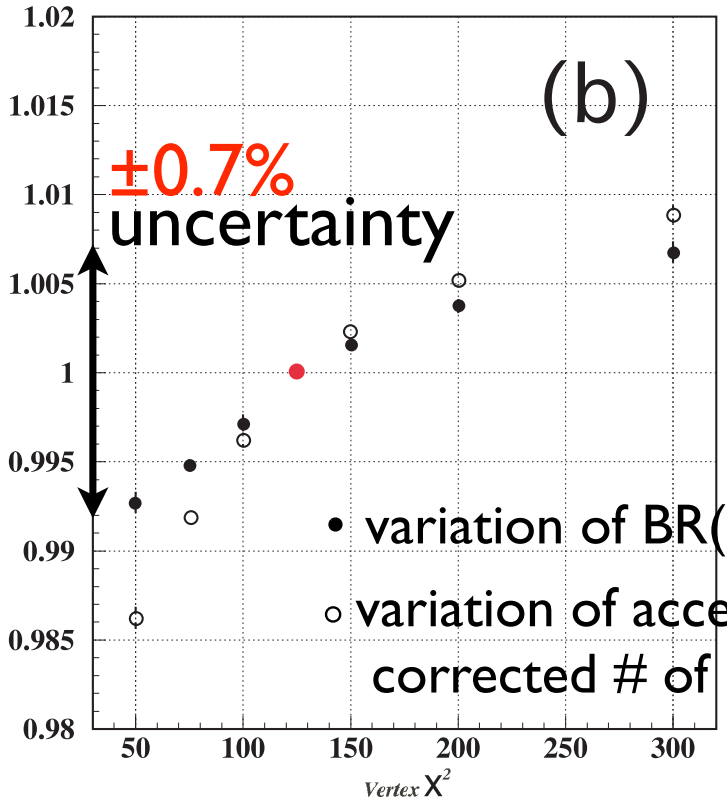


+0.4% uncertainty from these plots

vertex-χ^2



vertex χ^2 is not from double Ke3 nor cascade



Cut variation on the vertex χ^2

π missing by π-hadron interaction in TRD

I do not have any idea about the error of the GEANT simulation.

At the moment I estimate ±10% of error of the GEANT simulation.

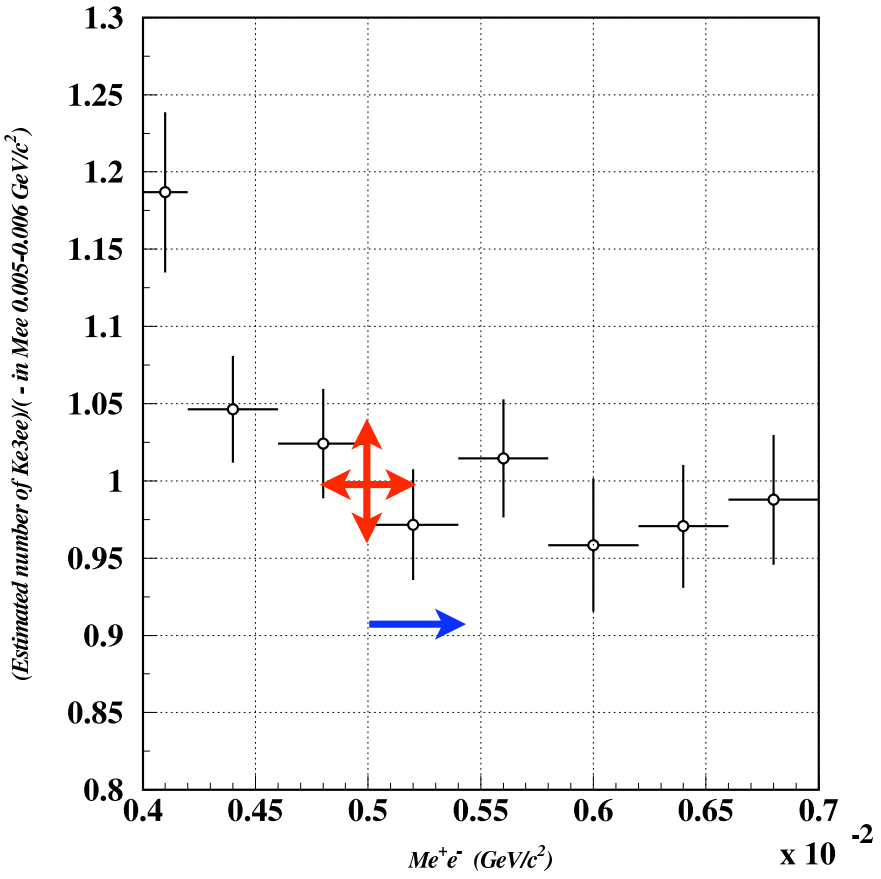
This error propagates as an ±0.47% of uncertainty of the BR(Ke3ee)

E_k distribution

The acceptance of Ke3ee varies between before and after the E_k tune.

This change corresponds to the -0.35% of BR(Ke3ee)

Mee cut-off



Conservatively,
the effect of lack of
< 0.004 GeV/c^2 events in
MC corresponds to
2% / (GeVc^{-2}) around
0.005 GeV/c^2.
It seems to continue
0.0054 GeV/c^2
This corresponds to
-0.18% of BR(ke3ee).

Result

Preliminary

BR(Ke3ee; Me^+e^- > 0.005 GeV/c^2)=

[1.606±0.012(stat.signal)

±0.003(stat.norm.)

$^{+0.026}_{-0.016}$ (systematic)

±0.045(external)]

$\times 10^{-5}$

	(%)
stat.signal	0.75
stat.norm.	0.19
systematic	1.62
	1.00
external	2.80